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ATTITUDE GROUND SUPPORT SYSTEM FOR THE SOLAR MAXIMUM MISSION SPACECRAFT

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ABSTRACT

The SMM Attitude Ground Support System (AGSS) supports the acquisition of spacecraft roll attitude reference, performs the in-flight calibration of the attitude sensor complement, supports onboard control autonomy via onboard computer data base updates, and monitors onboard computer (OBC) performance. Initial roll attitude acquisition is accomplished by obtaining a coarse 3-axis attitude estimate from magnetometer and Sun sensor data and subsequently refining it by processing data from the Fixed Head Star Trackers. In-flight calibration of the attitude sensor complement is achieved by processing data from a series of slew maneuvers designed to maximize the observability and accuracy of the appropriate alignments and biases. To ensure autonomy of spacecraft operation, the AGSS selects guide stars and computes sensor occultation information for uplink to the OBC. The onboard attitude control performance is monitored on the ground through periodic attitude determination and processing of OBC data in downlink telemetry. In general, the control performance has met mission requirements. However, software and hardware problems have resulted in sporadic attitude reference losses.

1. INTRODUCTION

The Solar Maximum Mission (SMM) spacecraft, first in the Multimission Modular Spacecraft (MMS) series, was launched on February 14, 1980. Seven payload instruments located in the SMM observatory study a large variety of solar-flare-related phenomena at the peak of the 11-year sunspot cycle. A summary of the experimental objectives of SMM is given by NASA GSFC (Reference 1). The SMM spacecraft components are shown in Figure 1. The attitude control objectives of SMM are to point the roll axis as defined by the experimenters as a result of coalignment to any point on the Sun's disk with an accuracy of ±5 arc-seconds and to maintain roll reference about the roll axis accurate to 0.1 degree. A comprehensive summary of the attitude determination and control functions as well as the attitude accuracy requirements for SMM are given by Guha (Reference 2). Notice, however, that the primary (roll) axis reference has been changed since then from the FPSS1 boresight to the experimenters' coalignment direction.

Ground attitude support for SMM is provided at the Goddard Space Flight Center (GSFC) by the Attitude Determination and Control Section (ADCS) and Computer Sciences Corporation. The major support functions are

- Acquisition of roll reference about the payload roll axis
- In-flight calibration of the attitude sensor complement consisting of two 3-axis magnetometers (TAMs), three 2-channel inertial reference units (IRUs), two Fine Pointing Sun Sensors (FPSSs), and two Fixed Head Star Trackers (FHSTs)
- Support of autonomous spacecraft operation under the control of an OBC for a period of up to 3 days

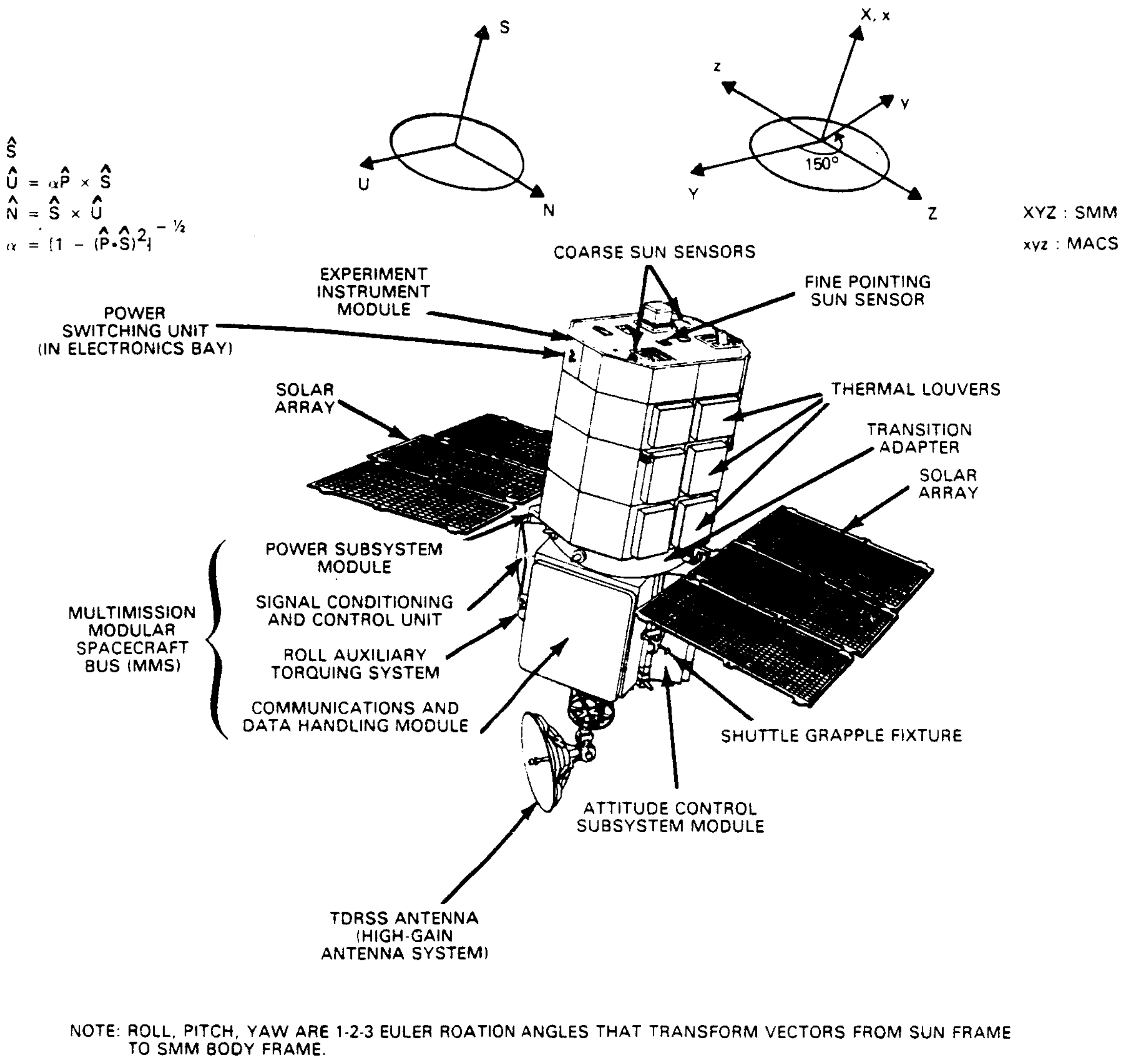

Figure 1. SMM Spacecraft Components

- Verification of the OBC attitude determination and control performance

This paper presents a broad overview of the ground support software and discusses the performance of the spacecraft attitude system and sensors in the postlaunch period. The relationship between OBC processing and the corresponding ground support is described. Contingencies and anomalous situations encountered during the postlaunch period are also presented.

2. FUNCTIONAL OVERVIEW OF THE SMM AGSS

The sensor configurations, coordinate systems, attitude acquisition, and sensor calibration algorithms used in the ground processing are described in detail in Reference 3. Descriptions of the algorithms for onboard attitude control are given by Markley (Reference 4). A functional block diagram illustrating the relationship between onboard and ground attitude processing is given in Figure 2.

Table 1 summarizes the major functions of the various components of the SMM AGSS. The software is operational on the IBM S/360 computer system at GSFC. The spacecraft telemetry data are processed in an interactive environment to monitor the health and safety of the spacecraft and to quality-assure the performance of the onboard attitude determination and control system.

3. SMM AGSS PERFORMANCE IN THE POSTLAUNCH PERIOD

The performance of the ground attitude system is discussed in this section.

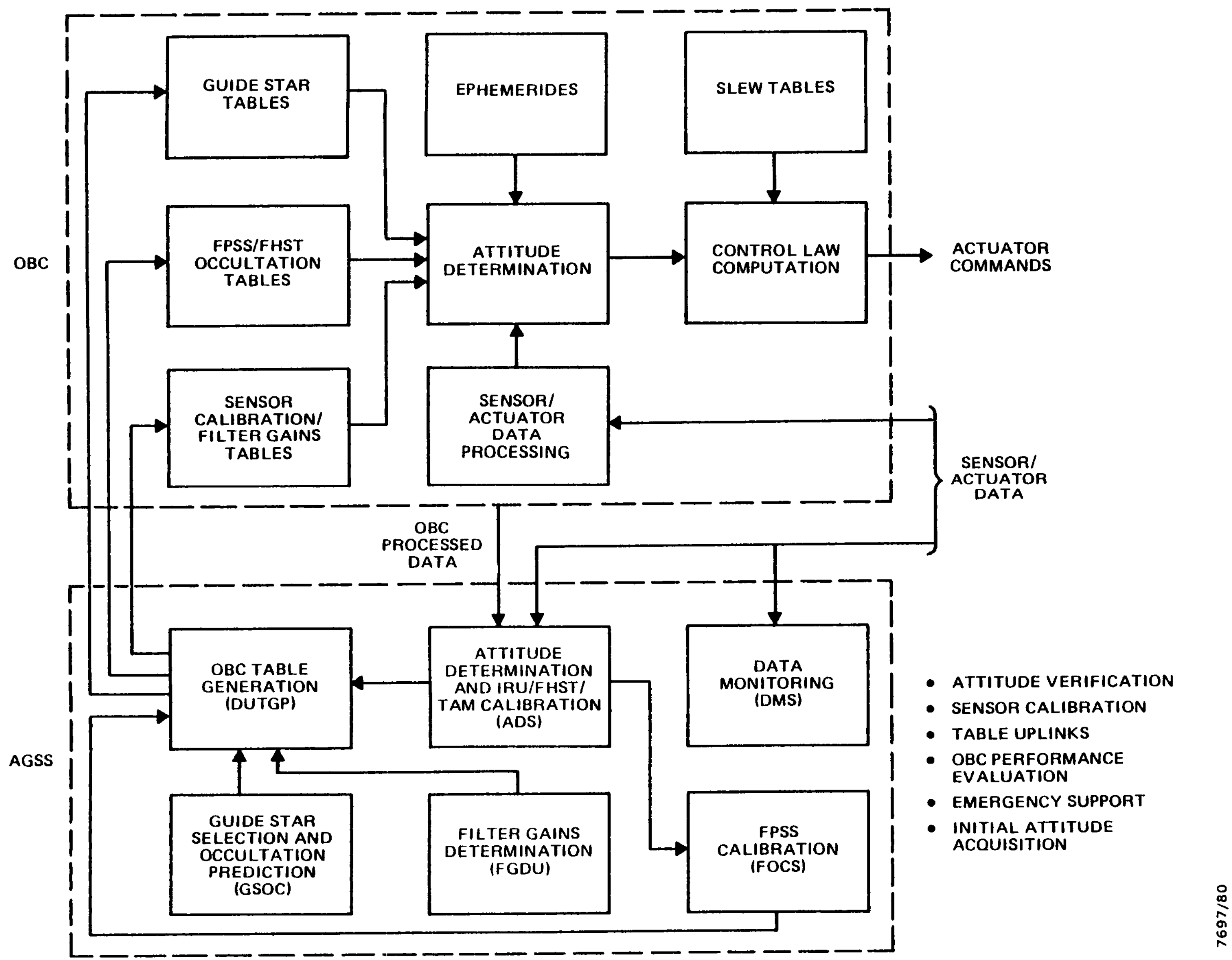

Figure 2. OBC and AGSS Attitude Processing Functional Block Diagram

Table 1. SMM Attitude Ground Support System

PROGRAM	FUNCTION
SMM/ADS	DETERMINES COARSE ATTITUDE TO AN ACCURACY OF 2 DEGREES FROM SUN AND MAGNETOMETER DATA. DETERMINES FINE ATTITUDE WITH SUN DATA TO AN ACCURACY OF BETTER THAN 5 ARC-SECONDS. DETERMINES FINE ATTITUDE WITH FHST DATA TO AN ACCURACY OF APPROXIMATELY 30 ARC-SECONDS. PERFORMS INITIAL ATTITUDE ACQUISITION AND SUPPORTS THE IN-FLIGHT CALIBRATIONS OF FHST, IRU, AND FPSS.
SMM/DMS	PERFORMS SENSOR AND OBC TELEMETRY DOWNLINK DATA MONITORING.
SMM/GSOC	SELECTS SUITABLE GUIDE STARS AND COMPUTES THEIR POSITIONS AND INTENSITIES IN THE FHST FIELD OF VIEW. PREDICTS OCCULTATIONS OF FHST AND FPSS BY THE EARTH, MOON, AND SOUTH ATLANTIC ANOMALY.
SMM/DUTGP	CONVERTS ENGINEERING DATA ON SENSOR CALIBRATION, GUIDE STARS, AND OCCULTATION PREDICTIONS INTO APPROPRIATE TABLE FORMAT FOR UPLINK TO THE ONBOARD COMPUTER.
SMM/FGDU	CALCULATES KALMAN FILTER GAIN MATRICES, CONTROL AND PROPAGATION MATRICES FOR ONBOARD ATTITUDE DETERMINATION AND CONTROL ESTIMATION.
SMM/FOCS	CALIBRATES THE FPSS IN THE OFF-NULL REGION. A NONLINEAR CALIBRATION CURVE IS FITTED TO THE FPSS DATA BY MINIMIZING THE RESIDUAL DIFFERENCES BETWEEN THE FPSS PITCH AND YAW ANGLES AND THE CORRESPONDING GYRO REFERENCE ANGLES. THE CALIBRATION ACCURACY IS BETTER THAN 2 ARC-SECONDS.

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3.1 INITIAL ATTITUDE ACQUISITION

Immediately after the launch, spacecraft control was under the safehold mode, in which data from the Coarse Sun Sensors (CSSs) were used to point the observatory roll axis to the Sun to within approximately 2 degrees. The spacecraft was placed under OBC control approximately 24 hours after launch. During this mode, the spacecraft was in an almost inertial orientation (the spacecraft roll axis tracks the Sun and, hence, moves approximately 1 degree per day) and data from the star trackers and IRU were available to determine 3-axis attitudes.

The primary procedure proposed for initial roll attitude acquisition consisted of two steps. In the first step, a coarse roll attitude is determined using the SMM/ADS subsystem. The coarse roll attitude, accurate to ±2 degrees, initializes the second step, fine roll attitude determination. The SMM/ADS computes fine roll solutions with an accuracy considerably better than the 0.1-degree mission requirement.

Several attempts to acquire fine roll attitude using the primary procedure were unsuccessful. Analysis showed that this was due to a misunderstanding in the definition of the star tracker coordinate system. This was verified by a careful analysis of the star motion in the camera fields of view during small slew maneuvers. After some investigation, the appropriate FHST documentation (Reference 5) was received and the correct tracker coordinate definition was established. The spacecraft roll attitude was established immediately thereafter.

3.2 SENSOR CALIBRATIONS

The in-flight calibrations of the attitude sensors are discussed in this subsection.

3.2.1 MAGNETOMETER CALIBRATION

The accuracy of coarse attitude determination is greatly improved by the in-flight determination of magnetometer biases. Magnetometer biases are determined by minimizing, in a least squares sense, the differences between the measured magnetic field magnitudes and those computed from a reference geomagnetic field model. The bias determination algorithm assumes that the magnetometer triad is orthogonal. It is of some interest to know the stability of these biases. The results of a long-term study of the SMM magnetometer biases are shown in Table 2. The bias B_x appears to be relatively stable and much larger in magnitude than the other biases; B_y and B_z are small but seem to reflect large fluctuations compared to their magnitude. This study indicates that to compute accurate attitudes, it is necessary to redetermine the biases at the time of attitude determination.

Table 2. Magnetometer Biases and Roll Attitudes

TIME (YYMMDD.HH)	MAGNETOMETER BIASES (MILLIGAUSS)			COARSE ROLL ATTITUDE (DEGREES)	TRUE ROLL (DEGREES)
	B_x	B_y	B_z		
800503.21	−66.4	−23.2	−18.5	−8.9	−7.8
800514.17	−72.9	−6.6	−5.1	0.5	0.0
800516.17	−70.6	−5.4	−2.7	1.8	0.0
800520.17	−85.2	3.3	3.8	−0.9	0.0
800522.17	−80.9	−1.5	22.3	13.1	12.7
800526.18	−68.6	3.3	0.6	0.4	0.0
800529.17	−72.9	14.6	−16.6	2.1	0.0
800604.12	−75.4	1.7	18.9	1.6	0.0

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It is believed that large, variable, uncompensated residual dipoles in the spacecraft contribute to the magnetometer biases. (SMM depends on the interaction between the geomagnetic field and torquer coils for momentum management.) However, the study also showed that the biases are relatively stable over a period of time of the order of a few orbits, and that reliable biases and coarse attitudes can be obtained if representative data points covering an entire orbit are processed. It is apparent from the results summarized in Table 2 that the accuracy of the coarse attitude determination is approximately 2 degrees when magnetometer biases are properly accounted for.

3.2.2 FHST/IRU/FPSS CALIBRATIONS

The SMM attitude sensors are calibrated so as to be consistent with each other. The FHST alignments and biases are determined using the output from the highly accurate FPSS. Attitudes determined from the calibrated FHSTs are then used to calibrate the IRUs. Finally, the off-null response of the FPSS is calibrated with reference to the IRUs.

It was noted during the early postlaunch period that the observed star separations in a given star tracker were different from the corresponding catalog star separations by as much as 35 to 90 arc-seconds. Moreover, attitudes determined from star data differed by as much as 100 arc-seconds from the FPSS reference attitudes. Consequently, an attempt was made to adjust the star tracker scale factor to reduce this discrepancy. Satisfactory results were obtained after this adjustment, which resulted in closer agreement with FPSS-measured attitudes (to within approximately 30 arc-seconds). A detailed account of the FHST alignment calibration as well as refinement of the prelaunch scale factors is given in References 6 and 7.

The IRU scale factor correction/alignment matrix and the 3-axis drift rates are determined by minimizing, in a least squares sense, the differences between IRU-propagated attitudes and the attitudes calculated using star and Sun data. There has been relatively little change in the IRU alignment in the postlaunch period. However, because of the failure of one of the three gyros, the primary gyro configuration was changed on September 1, 1980. A detailed account of the SMM IRU calibration is given in Reference 6.

The coefficients of the FPSS digital-to-analog nonlinear transfer function were determined by minimizing the residuals between the changes in pitch and yaw angles computed from FPSS measurements and the corresponding reference attitude changes obtained from IRU measurements of slew maneuvers executed to cover the FPSS field of view (References 6) and 8). The FPSS calibration accuracy was better than 1.2 arc-seconds in all instances. However, some degradations were observed in the FPSS, as discussed in the next subsection.

It is believed that the overall fine attitude determination accuracy with calibrated star tracker data is approximately 30 arc-seconds each in roll, pitch, and yaw, and with calibrated FPSS data is better than 5 arc-seconds in pitch and yaw.

3.2.3 RECALIBRATION OF FINE POINTING SUN SENSORS

Attitudes measured with FPSS1 and FPSS2 have been monitored regularly during the postlaunch period. As shown in Figure 3, the telemetry transfer function of the FPSS has been slowly changing with time, especially in the off-null region. To reduce the impact of these degradations and to ensure that the pitch and yaw pointing accuracy requirements are met, FPSS recalibration activities are being conducted on a regular basis.

Slew data to calibrate the FPSS were collected on March 4, June 21, July 10, August 1, and August 25, 1980. The first set of FPSS calibration parameters was uplinked on March 18, 1980. The second set of refined FPSS calibration parameters was uplinked with the new OBC flight software (version 13h) on July 31, 1980.

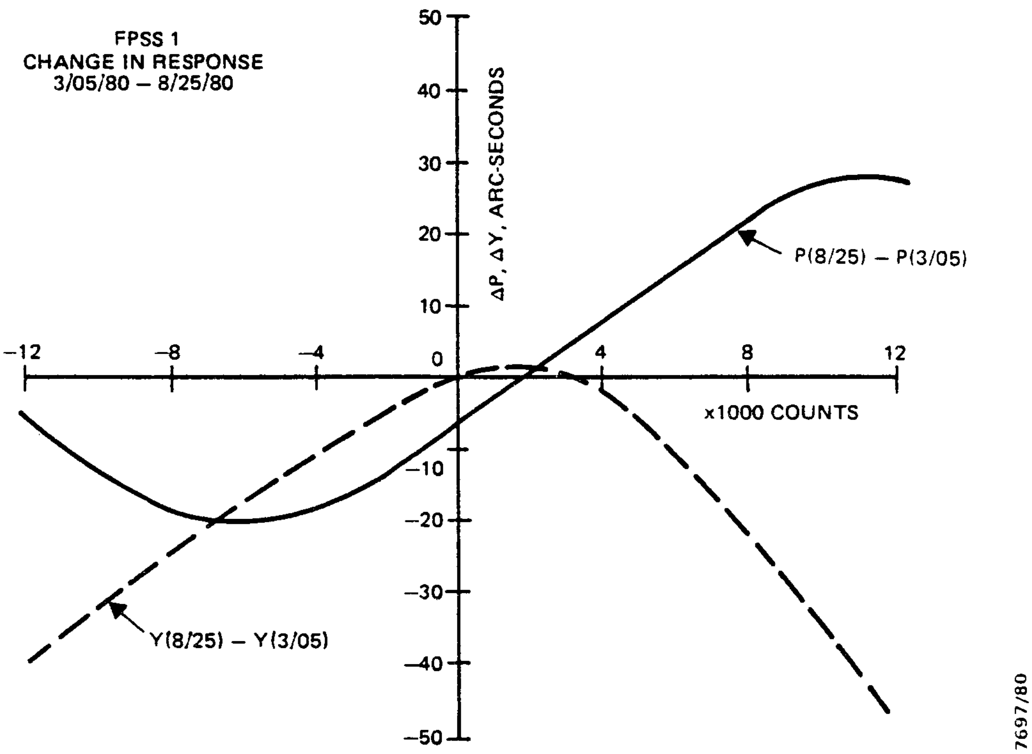

Figure 3. Change in Response of FPSS1 with Time as Measured by the Telemetry Function in the Field of View

3.3 GUIDE STAR SELECTION

The difference between the observed and predicted positions of the guide stars in the star tracker field of view is used by the SMM control system to estimate the drift rates of the roll axis gyros. The major criteria used for the selection of guides stars are the following:

- Stars must remain within the FHST field of view during the entire period (nominally 3 days).
- Because of the finite size of the search area in the field of view, the star must be isolated within a fixed angular region (nominal tolerance of 1.15 degrees vertically and 1.10 degrees horizontally).

A more detailed account of the guide star selection criteria is given in Reference 6.

It was known from prelaunch studies that there would be periods of guide star scarcity during the SMM mission lifetime. Relaxing the criteria mentioned above to reduce the duration of the period to approximately 2 days and/or reducing the near-neighbor tolerance window slightly have worked successfully during most of these periods. In one instance (September 18, 1980, through September 23, 1980), it was necessary to change the nominal null roll attitude to -90 degrees in roll to guarantee the availability of guide stars.

It was also observed during the mission that the intensity responses of the trackers were somewhat different from those indicated by prelaunch calibrations. Thus, an in-flight intensity calibration of the trackers was performed (Reference 6), which resulted in more reliable guide star acquisitions by the OBC.

3.4 OCCULTATION PREDICTION

FPSS occultation predictions were biased to shorten the orbit day to avoid erroneous triggering of the attitude acquisition mode during day/night or night/day transitions. A similar procedure was adopted for FHST occultation predictions to prevent bad data from being processed by the OBC.

In general, no problems were encountered in the occultation prediction function. No measurable star data degradation was observed during the periods when the spacecraft passed through the regions of South Atlantic Anomaly.

4. SMM OBC PERFORMANCE MONITORING ON THE GROUND

4.1 PITCH/YAW POINTING CONTROL

Pitch and yaw pointing accuracy of the SMM observatory are frequently monitored. The results of a pitch/yaw slewing accuracy verification test, conducted with data taken on June 26, 1980, are presented in Table 3. It can be clearly seen that the relative slewing accuracy of the SMM control system using calibrated gyros and FPSS is within the accuracy requirements of 5 arc-seconds for the mission.

Table 3. SMM Control System Slewing Accuracy Verification

TIME (800626)		ΔPITCH (ARC-SECONDS)		PITCH ERROR (ARC-SECONDS)
START	STOP	FPSS1	GYRO	
0.083830	0.083859	−485.6	−486.3	0.7
0.084028	0.084109	822.7	821.8	0.9
0.084427	0.084516	−1641.2	−1640.5	0.7
0.084824	0.084918	1641.3	1644.8	3.5
0.085225	0.085312	−822.8	−820.4	2.4

TIME (800626)		ΔYAW (ARC-SECONDS)		YAW ERROR (ARC-SECONDS)
START	STOP	FPSS1	GYRO	
0.083928	0.084002	483.0	481.4	1.6
0.084226	0.084258	782.0	781.1	0.9
0.084628	0.084717	−1602.0	−1602.6	0.6
–	–	–	–	–
–	–	–	–	–

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4.2 ROLL POINTING CONTROL

The roll reference accuracy is well within the 0.1-degree mission requirement. Roll control has been maintained throughout, except on the occasions mentioned in Section 4.4. Roll slewing accuracy has also been monitored on the ground. For example, using calibrated gyros for a commanded roll of 90 degrees on August 1, 1980, the measured roll attitude difference was 89.98 degrees. Thus, the roll slew error is 0.02 degree--well within the 0.1-degree roll accuracy limit of the mission.

4.3 OBSERVATION OF A SPACECRAFT CONTROL ANOMALY NEAR ORBIT DUSK

A spacecraft control anomaly was observed at approximately 10 minutes before orbit dusk on June 30, 1980, when the gyros indicated a pitch change of approximately 10 arc-seconds while the pitch output from FPSS1 remained steady. Results from an extensive search of data dating back to the immediate postlaunch period summarized in Table 4 indicated that a probable cause of this problem could be the degradation of FPSS1 data due to the reflection of Earth albedo from a thermal vent, and the subsequent attempt by the onboard control system to compensate for this degradation by slewing the spacecraft.

Table 4. SMM Pitch/Yaw Control Anomalies Near Orbit Dusk

ORBIT DAWN (YYMMDD.HHMM)	TIME OF MAXIMUM GYRO SLEW FROM ORBIT DAWN (MINUTES)	ROLL ANGLE (DEGREES)	MAXIMUM FPSS2 DEVIATION (ARC-SECONDS)	MAXIMUM GYRO DEVIATION (ARC-SECONDS)
800223.1710	56	0	0.6 (PITCH)	7.2 (PITCH)
800327.1832	54	0	1 (PITCH)	
800429.1941	54	0		10.4
800522.2044	55	−12	0.2 (PITCH)	5.4 (PITCH)
800527.1902	52	0	0.3 (PITCH)	3.6 (PITCH)
800606.1703	59	180	0.5 (YAW)	7.2 (PITCH)
800614.1520	58	−90	0.2 (YAW), 1.3 (PITCH)	3.6
800630.1801	54	0	1.5 (PITCH)	10.4 (PITCH)
800708.1744	53	0	1 (PITCH)	
800709.1741	54	0	1 (PITCH)	7.9 (PITCH)

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An operational workaround for this problem was devised by increasing the FPSS occultation times duration in the OBC data base so that during the projected periods of potential anomalies, the control system enters the night mode--gyro reference--of control.

4.4 SPACECRAFT CONTINGENCIES

During the period from April 4, 1980, to September 1, 1980, the spacecraft lost attitude control 14 times. Guide star losses and OBC gyro drift update software problems caused half of these spacecraft contingencies. The remaining were directly attributable to other OBC problems. Table 5 gives a brief summary of these contingencies. Additional information is available in Reference 6.

Table 5. Spacecraft Control Problems During April 4, 1980 through September 1, 1980

NO.	DATE	NATURE OF PROBLEM	GROUND RESPONSE	COMMENTS
1	4/4/1980	ROLL REFERENCE LOST	ROLL ATTITUDE REACQUIRED	TIME JUMP IN S/C CLOCK
2	4/27/1980	ROLL REFERENCE LOST TEMPORARILY	MONITORING; ROLL REACQUISITION	TIME JUMP IN S/C CLOCK
3	5/2/1980	SAFEHOLD MODE	MONITORING AND ROLL REACQUISITION	PROBABLE TELEMETRY INTERFACE PROBLEM
4	5/10/1980	ROLL/PITCH/YAW REFERENCE LOST	THREE-AXIS ATTITUDE ACQUISITION	OBC SOFTWARE PROBLEM RELATED TO SUNSPOT TRACKING WHILE SLEWING
5	5/22/1980	ROLL/PITCH/YAW REFERENCE LOST	THREE-AXIS ATTITUDE ACQUISITION	OBC SOFTWARE PROBLEM
6	5/31/1980	GUIDE STAR LOST	GUIDE STAR TABLE REGENERATED	FHST2 STAR INTENSITY PROBLEM
7	6/13/1980	ROLL REFERENCE LOST	ROLL ATTITUDE REACQUIRED	ROLL GYRO DRIFT UPDATE PROBLEM
8	6/18/1980	GUIDE STAR LOST	GUIDE STAR TABLE REGENERATED	FHST2 INTENSITY PROBLEM
9	6/19/1980	ROLL REFERENCE LOST	ROLL REACQUIRED	ROLL GYRO DRIFT UPDATE PROBLEM
10	6/30/1980	SAFEHOLD MODE	ROLL ACQUISITION	OBC NEW FLIGHT SOFTWARE
11	8/1/1980	GUIDE STAR LOST	GUIDE STAR TABLE REGENERATED	FHST2 INTENSITY PROBLEM
12	8/4/1980	ROLL REFERENCE LOST	ROLL REACQUIRED	STAR PROCESSOR ON OBC WAS DISABLED
13	8/7/1980	ROLL REFERENCE LOST	ROLL REACQUIRED	PROBABLE OBC SOFTWARE PROBLEM
14	9/1/1980	SAFEHOLD MODE	THREE-AXIS ATTITUDE ACQUISITION	GYRO FAILURE; NEW GYRO CONFIGURATION RIPIYI

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5. CONCLUSIONS

The major conclusions based on the ground attitude support activities for SMM are as follows:

- Coarse attitude solutions accurate to within ±2 degrees were obtained from CSS and magnetometer data corrected for magnetometer biases that were determined for the particular data interval. These biases have shown appreciable time dependence.
- Fine attitude solutions accurate to approximately 30 arc-seconds were obtained with calibrated star tracker data. Pitch/yaw attitude solution accuracy was better than 5 arc-seconds using calibrated FPSSs.
- Star data sampling frequency (approximately 15 data points per minute) was comparatively low. The number of data points collected for each star varied from 4 to 15. The higher number of data points yielded better attitude estimates.
- In general, the guide star selection function worked very well. Periods of guide star scarcity were anticipated in advance and dealt with successfully.
- The sensor occultation function worked satisfactorily. Predicted periods were usually within 15 seconds of observed periods.
- Sensor calibration functions were performed reliably; self-consistent and accurate calibration parameters were generated. Overall pointing accuracy using calibrated sensors was better than 3.5 arc-seconds in pitch and yaw and better than 0.05 degree in roll.

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